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14. ABSTRACT
This presentation examines the propagation and properties of acoustic disturbances caused by cavitating venture at different operating regimes. Issues of interest are effects on cold flow and water visualization jets (injectors) and the Big Picture: LRE systems. There is a lack of literature pertaining to unsteady characteristics. Theory is explored, along with test details for design space, test facility, test apparatus, and preliminary results.

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Summer Co-op Outbrief:
Themis Cavitating Venturi Resonance Study

Phuoc Hai Tran
Research Engineer Summer Intern
AFRL/RZSE/JNT

Biography

- **Phuoc Hai N. Tran**
  - Henry Samueli School of Engineering & Applied Science, University of California: Los Angeles
    - Aerospace Engineering B.S. (2013) in progress
    - UCLA AIAA HyPE Rocket Project
    - UCLA Energy Innovation Laboratory
    - 2010–2011 Vishal Parikh Memorial Scholarship Recipient
      - For outstanding academic achievement coupled with a strong interest in the field of Rocket Propulsion.
  - Interests
    - Jet Propulsion, Fluid Dynamics, Aerodynamics
    - Aerospace (Rocketry/Aviation), Cars, Computer Technology, Photography

Study Introduction

Background and Theory

Background and Relevance

<u>Research Objective:</u>

❖ *Examine the propagation and properties of acoustic disturbances caused by cavitating venturi at different operating regimes*

Fig1. Insert-type Cavitating Venturi Profile
(AFRL/RZOP, 2011)

- **Extensive use in LREs**
  - Precise passive flow rate control
    - Themis Cold Flow
    - Themis Water Visualization Study
  - System isolation
    - Combustion instability mitigation
- **Issues of interest**
  - Effects on cold flow and water visualization jets (Injectors)
  - Big Picture: LRE systems
- **Lack of literature pertaining to unsteady characteristics**

Theory

- **Mass Flow Rate derived from Bernoulli's Equation**
  - Dependent only on P_1 and P_v

$$\dot{m} = C_d A_{th} \sqrt{2\rho(P_1 - P_v)}$$

- **Flow is "choked" through a combination of phenomena**
  - Occurs when $R_p \sim 0.85$
  - Independent of P_2 and any changes to downstream pressure

- **Dimensionless Variables**

Cavitation Number | Pressure Ratio

$$\sigma = \frac{P_1 - P_v}{P_1 - P_2} \qquad R_P = \frac{P_2}{P_1}$$

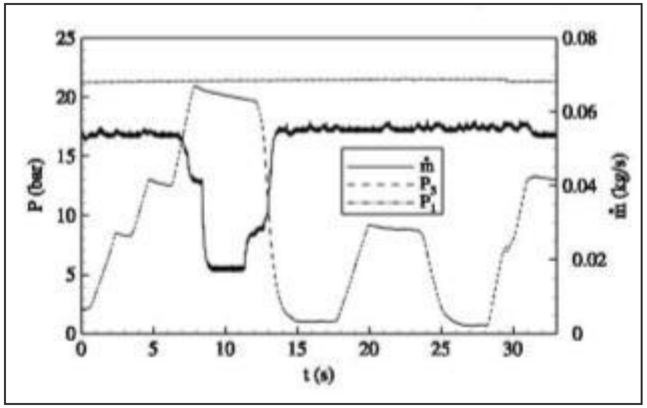


Fig2. Mass Flow and Pressure Ratio versus Time
(Ghassemi & Fasih, 2011)

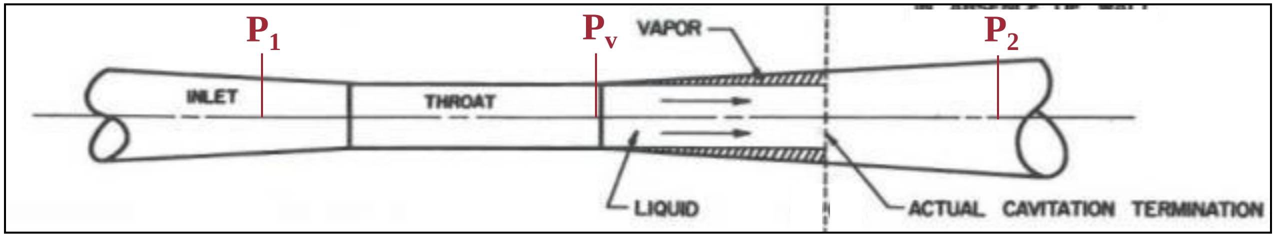


Fig3. Detailed Typical Venturi Cross Section
(Hammitt & Robinson, 1966)

Theory

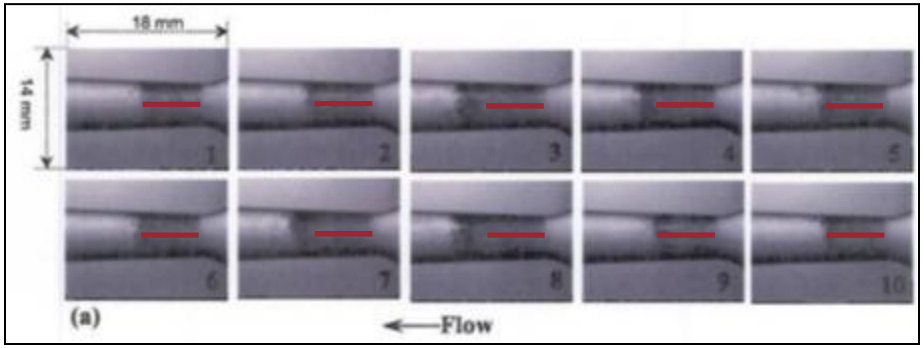


Fig4. Cavitation Length Fluctuation Over Time
(Sayyaadi, 2010)

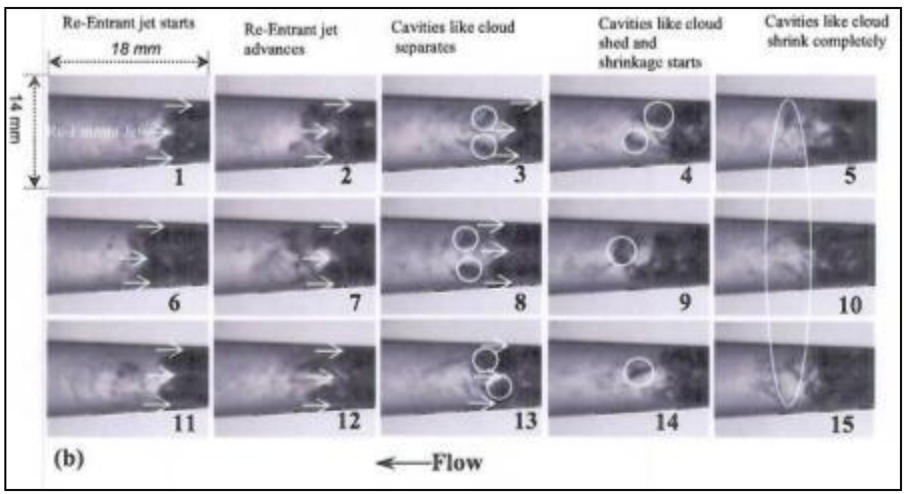


Fig5. Unsteady Flow Phenomena at Cavitation Front
(Sayyaadi, 2010)

- **Inherently unsteady process**
- **Sparse data and results**
  - Poor frequency response of static pressure and mass flow sensors
  - Difficult to model in CFD
  - Disparity between experimental and computational studies
- **Strouhal number** $St = \frac{f L_c}{V_{th}}$
  - Characterize disturbances
  - Function of cavitation number
  - Range of 0.015 to 0.45 (depending on literature source)

Test Details

Design and Implementation

Design Space

- **Test Variables**
  - Upstream pressure [$\mathbf{P_1}$]
  - Downstream (Back) pressure [$\mathbf{P_2}$]
  - Venturi Geometry
- **Test Measurements**
  - Pressure Readings
    - Fluctuations at pressure stations of varying L/D position
  - Mass Flow Rate
    - Catch and weigh
- **Sample Conditions**
  - 0.035" ID, 1.3" L_c, 800 psi P_1
    - Frequency Range: 60 to 1400 Hz
    - Throat Dynamic Pressure: 799 psi
    - Mass Flow Rate: 0.144 lbm/sec
- **Instrumentation Selection**
  - Kistler 603B1 with 223A Adapter
    - Wall Flush, Dynamic Reading
    - Easily resolves frequency
    - Easily handles pressure spikes
  - Kistler 5010B Dual Mode Amplifier
    - Select pressure range
- **Issues and Constraints**
  - Time, Cost, Availability

Pressure Range	psi	15000
Calibrated Partial Range	%	1, 10
Maximum Pressure without damage	psi	18000
Sensitivity nom.	pC/psi	−0.35
Threshold (charge amplifier noise)	psi	0.01
Amplitude Non-linearity zero based BFSL	%FSO	±1
Hysteresis	%FSO	1
Insulation Resistance at R.T.	Ω	10^{13}
Resonant Frequency nom.	kHz	500

Fig6. Kistler 603B1 Technical Data Excerpt
(Kistler Instrumentation Corp., 2003)

Design Space

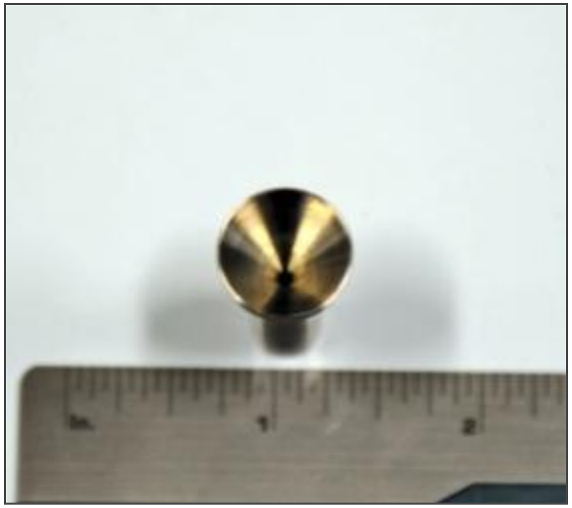


Fig8. Venturi Inlet (0.047”)
(AFRL/RZOP, 2011)

Fig9. Venturi Profile (0.047”)
(AFRL/RZOP, 2011)

Fig10. Venturi Outlet (0.047”)
(AFRL/RZOP, 2011)

D_{throat}	$D_{exit, outer}$	$D_{exit, inner}$	$D_{inlet, outer}$	Wall $Thickness_{inlet}$	$D_{inlet, inner}$	L_{total}	L_{inlet}	L_{exit} (L_c)
0.047	0.3435	0.1829	0.6272	0.0161	0.595	1.2348	0.2512	0.9836
0.0595	0.3761	0.2185	0.6549	0.0147	0.6255	1.4934	0.2348	1.2586
0.027	0.3432	0.1899	0.6258	0.0149	0.596	0.8652	0.258	0.6072

Fig11. Venturi Dimensions
(Phuoc Hai Tran AFRL/RZSE, 2011)

Design Space

- **Simple Cases**
  - Vary only by R_p
    - Set only "Back Pressure" during runs
- **Wide Data Range**
  - Many comparisons possible
  - Spaced for wide σ and R_p spread
- **Case Overview**
  - 3 Venturi inserts
  - 4 Inlet pressures
  - 17 Back pressures
  - <u>204 Test runs</u>
  - <u>15 Seconds per pressure data run</u>
  - <u>5 Minutes per venturi mass flow run</u>
  - <u>10 Minute venturi recycle time</u>

Inlet Pressure	Back Pressure	Cavitation Number	Pressure Ratio
1500	1406.3	15.99	0.94
	1387.5	13.33	0.93
	1368.8	11.42	0.91
	1350.0	10.00	0.90
	1312.5	8.00	0.88
	1275.0	6.66	0.85
	1237.5	5.71	0.83
	1200.0	5.00	0.80
	1125.0	4.00	0.75
	1050.0	3.33	0.70
	975.0	2.86	0.65
	900.0	2.50	0.60
	750.0	2.00	0.50
	600.0	1.67	0.40
	450.0	1.43	0.30
	300.0	1.25	0.20
	150.0	1.11	0.10

Inlet Pressure	Back Pressure	Cavitation Number	Pressure Ratio
1000	937.5	15.99	0.94
	925.0	13.33	0.93
	912.5	11.42	0.91
	900.0	10.00	0.90
	875.0	8.00	0.88
	850.0	6.66	0.85
	825.0	5.71	0.83
	800.0	5.00	0.80
	750.0	4.00	0.75
	700.0	3.33	0.70
	650.0	2.86	0.65
	600.0	2.50	0.60
	500.0	2.00	0.50
	400.0	1.67	0.40
	300.0	1.43	0.30
	200.0	1.25	0.20
	100.0	1.11	0.10

Fig7. Experiment Test Matrix
(Phuoc Hai Tran AFRL/RZSE, 2011)

Test Facility

- **1-14 Flow Lab**
  - Test medium
    - Deionized water
  - System capabilities
    - Upstream run pressures of up to 2000 psi via regulator
    - Downstream run pressure down to 14 psi via throttle valve
    - Flow Rate of up to ~20 gpm
    - Water degasification system
  - Main systems
    - Water tank pressurize
    - Water tank degasify
    - Water tank fill
    - Water run
  - <u>Fast recycle time</u>

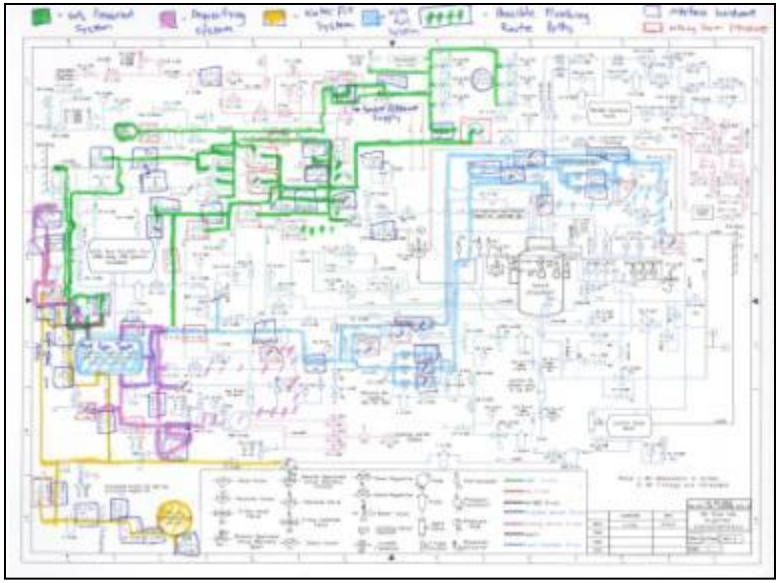


Fig12. Flow Lab PID with Main Systems
(Edgar Felix AFRL/RZSA, July 2011)

- **Safety Considerations**
  - Pressurized vessels
  - High noise level
    - Venturi ringing
    - Line and tank venting

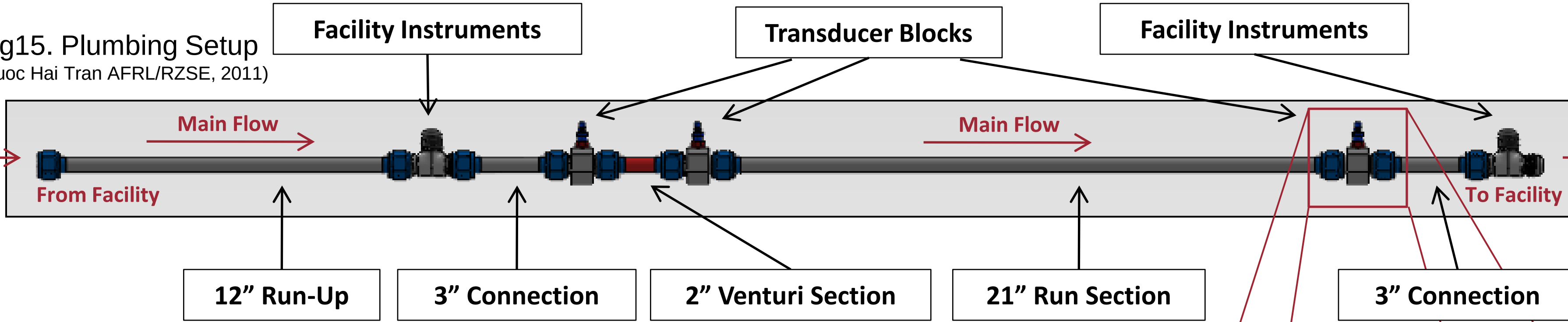
Test Facility

Fig13. Main Water Tank and Line Pressurization Regulators
(AFRL/RZOP, 2011)

Fig14. Water Tank and Rear Pressure Regulator Panel
(AFRL/RZOP, 2011)

Test Apparatus

Fig15. Plumbing Setup
(Phuoc Hai Tran AFRL/RZSE, 2011)



- **Hardware**
  - 0.049” Wall stainless steel AN-08
    - Rated to over 3500 psi
  - Integrated into 1-14 Flow Loop
    - (~ 38 L/D) 6’ total length
    - (~ 48 L/D) ~17” Run-up to Venturi
    - ~23” Run to downstream block

- **Instrumentation**
  - Facility Instruments (Not Shown)
    - AN-08 Cross
    - AN-08 Tee
    - 2x Static PTs
    - 1x Thermocouple
  - 3x Transducer Blocks
    - Custom design
    - AN-08, 304 Stainless
    - Wall flush
    - Dynamic PTs

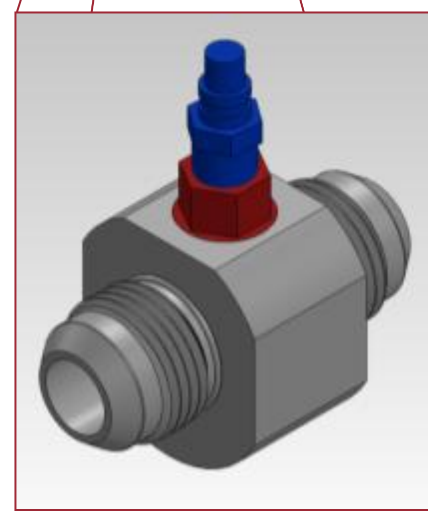


Fig16. Transudcer Block with PT
(Phuoc Hai Tran AFRL/RZSE, 2011)

Test Apparatus

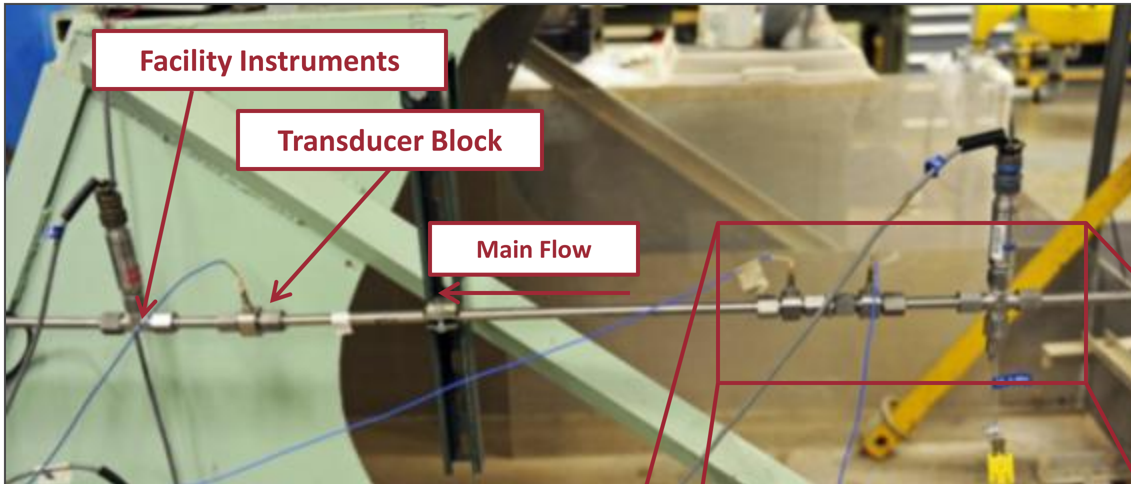


Fig17. Test Apparatus in Flow Loop
(AFRL/RZOP, 2011)

Fig18. Kistler 5010B Signal Processing Units
(AFRL/RZOP, 2011)

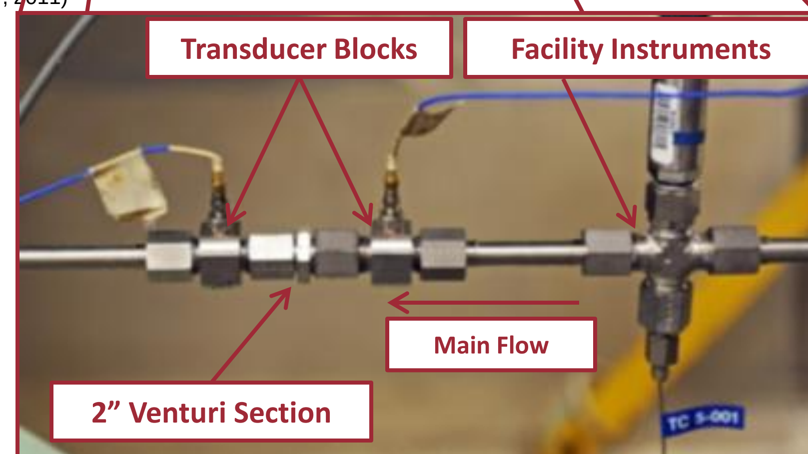


Fig19. Close-up of Venturi Section with Transducer Blocks with fitted Kistler 6031B Transducers
(AFRL/RZOP, 2011)

Preliminary Results

Cavitating Region Characteristics

Test Notes & Observations

- **DAQ Sampling Selection: 2 seconds @ 100,000 Hz**
  - Sampling rate high enough to resolve frequencies
  - Sample length long enough for multiple analyses
- **Amplifier Scale adjusted for optimum resolution**
  - Varied between runs according to flow regime
- **Audible flow regime transitions**
- **Mass flow measurements**
  - 750psi case discarded in the interest of time
  - Anomalous 0.0595" Venturi mass flow results

Analysis Notes

- **High frequency raw data in mV**
  - Convert to psi using correct scale

- **Pressure amplitude (psi) data**
  - Take mean of absolute value of converted pressure data

- **Frequency signatures of raw data**
  - Fast Fourier Transform (FFT) on each data set
    - 4096 samples, 50 runs each, frequency resolution of ~24 Hz

System Baseline

- **Flow through apparatus without venturi**
- **Lower frequency modes**
  - Spectra resembles that of turbulent flow
- **Similar frequency modes in non-cavitating test runs**
  - Dominated by lower frequency modes
- **Low average pressure amplitude**
  - Order of 1.0 psi

System Baseline

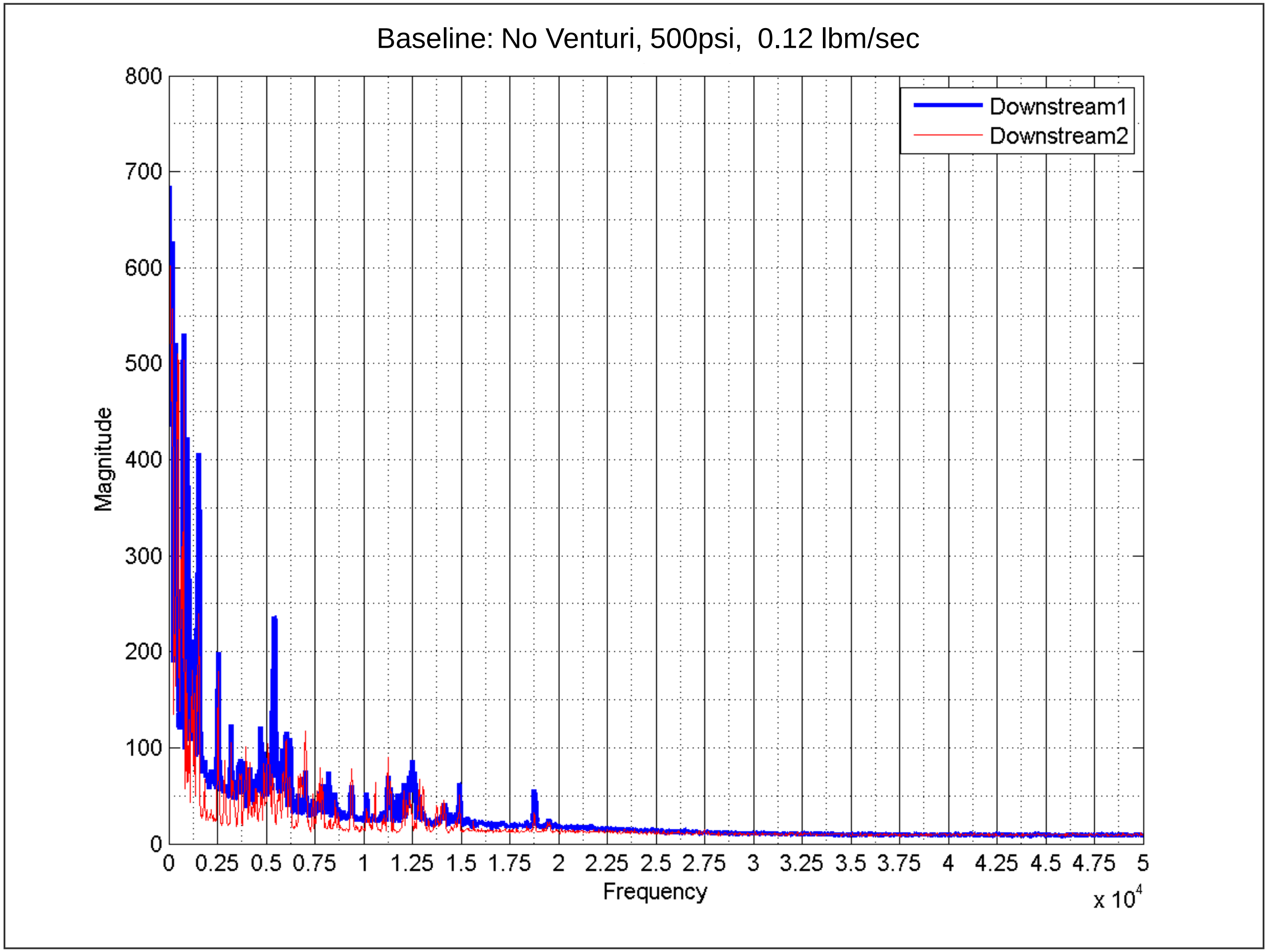


Fig20. Baseline FFT Plot

(Phuoc Hai Tran AFRL/RZSE, 2011)

System Baseline

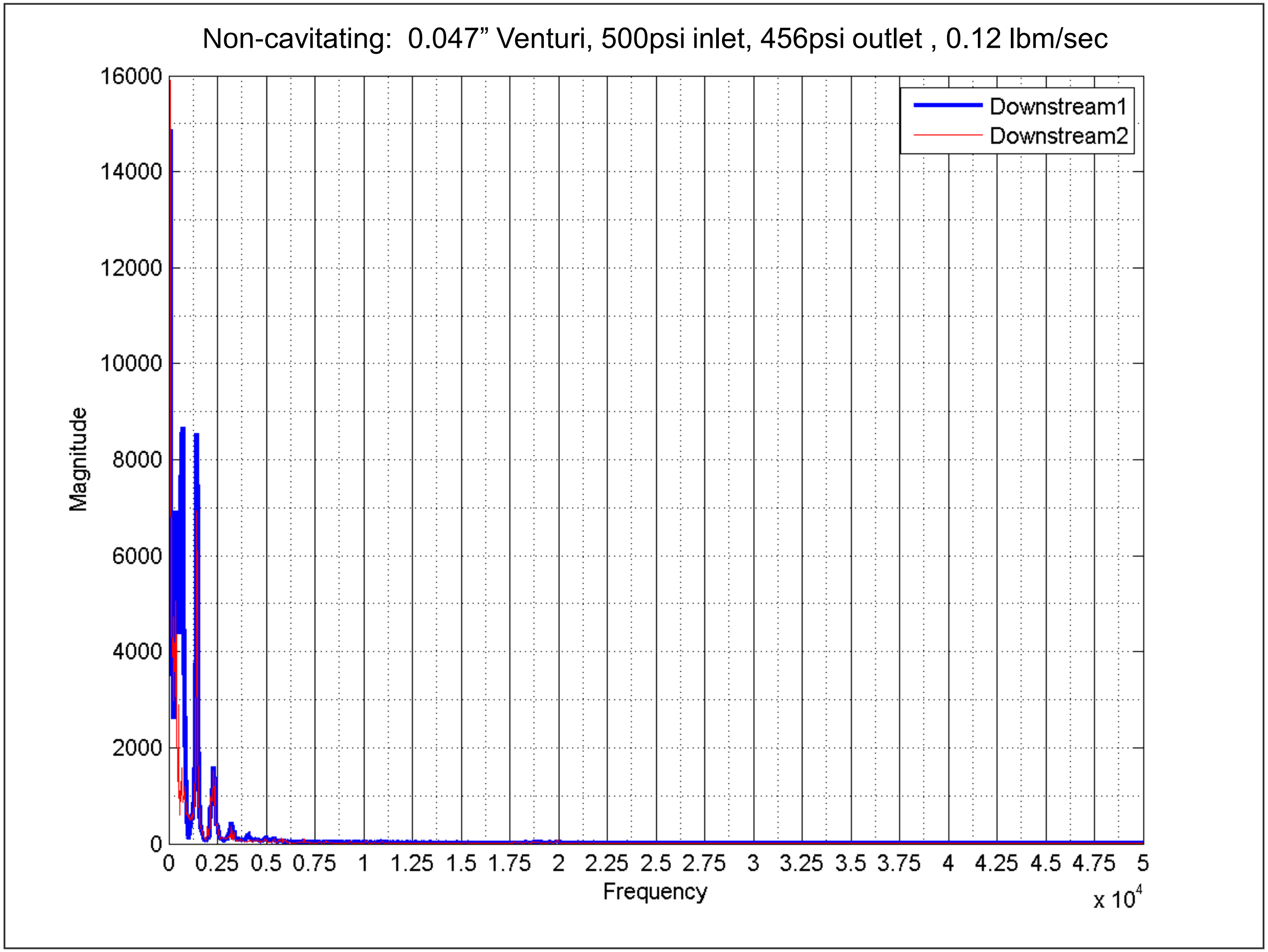


Fig21. Non-cavitating FFT Plot
(Phuoc Hai Tran AFRL/RZSE, 2011)

Pressure Amplitudes and Attenuation

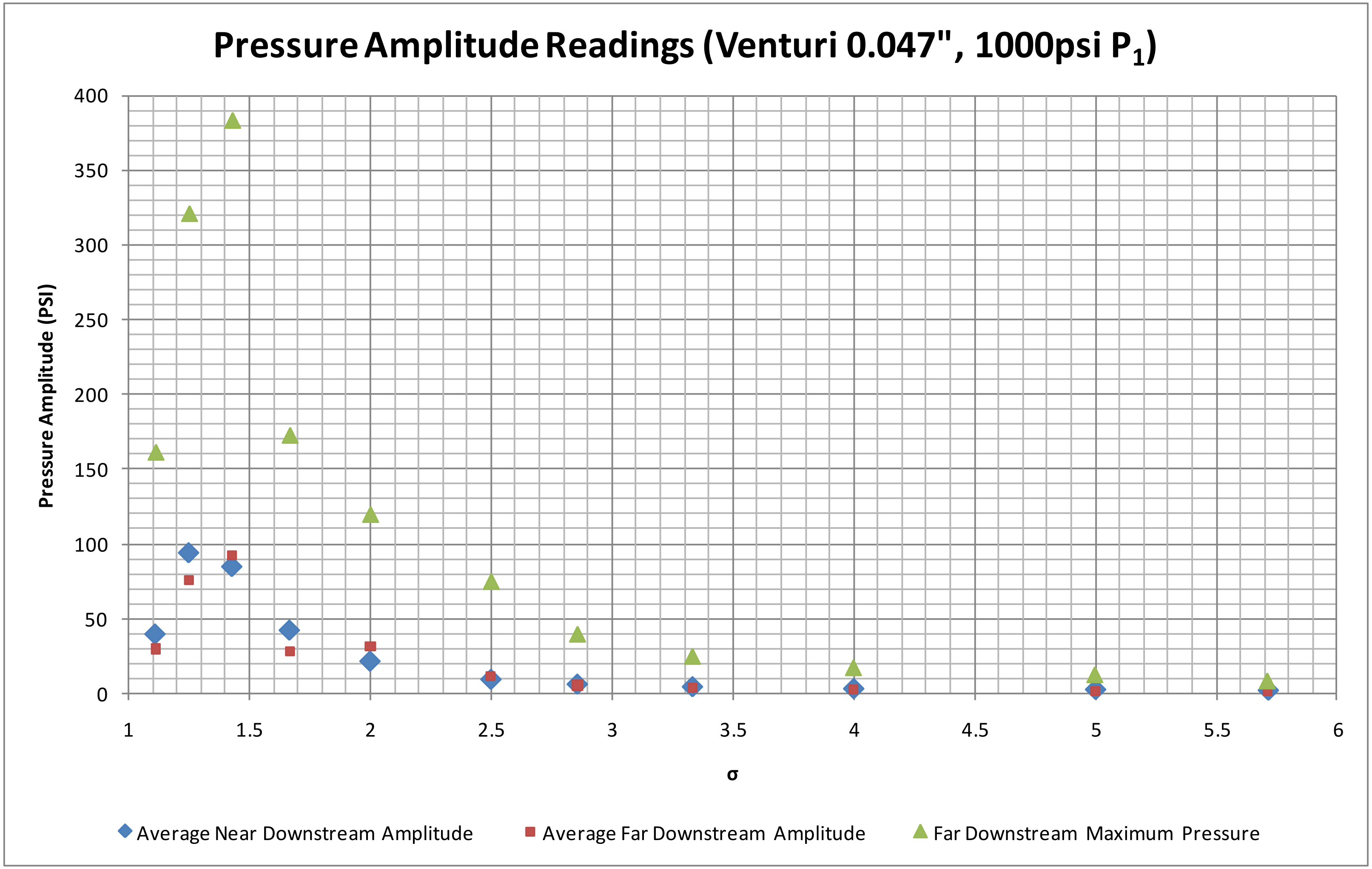


Fig22. Pressure Amplitude Plot
(Phuoc Hai Tran AFRL/RZSE, 2011)

Frequency Analysis

$$St = \frac{f L_c}{V_{th}}$$

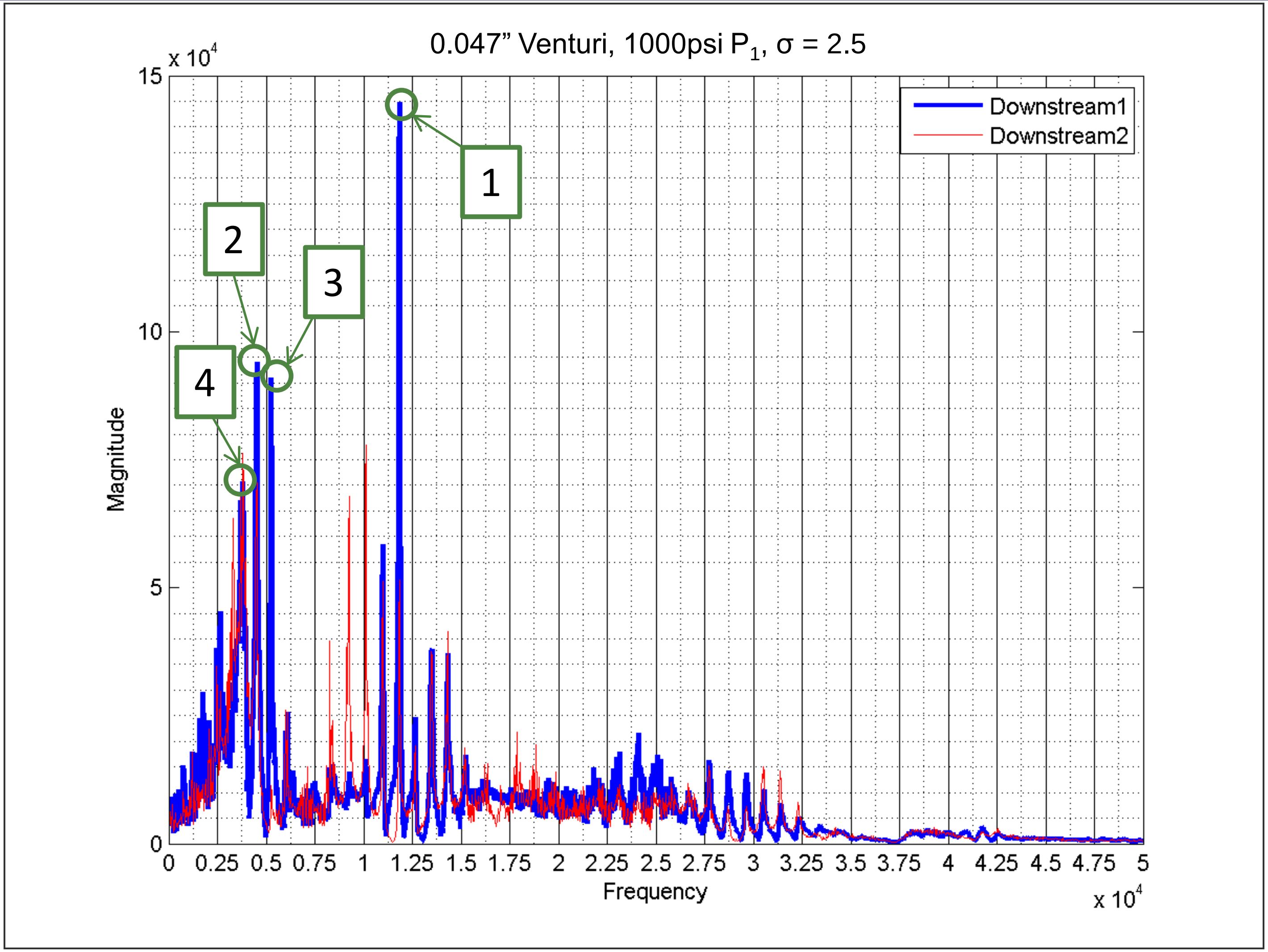


Fig23. FFT Sample Analysis

(Phuoc Hai Tran AFRL/RZSE, 2011)

Frequency Analysis

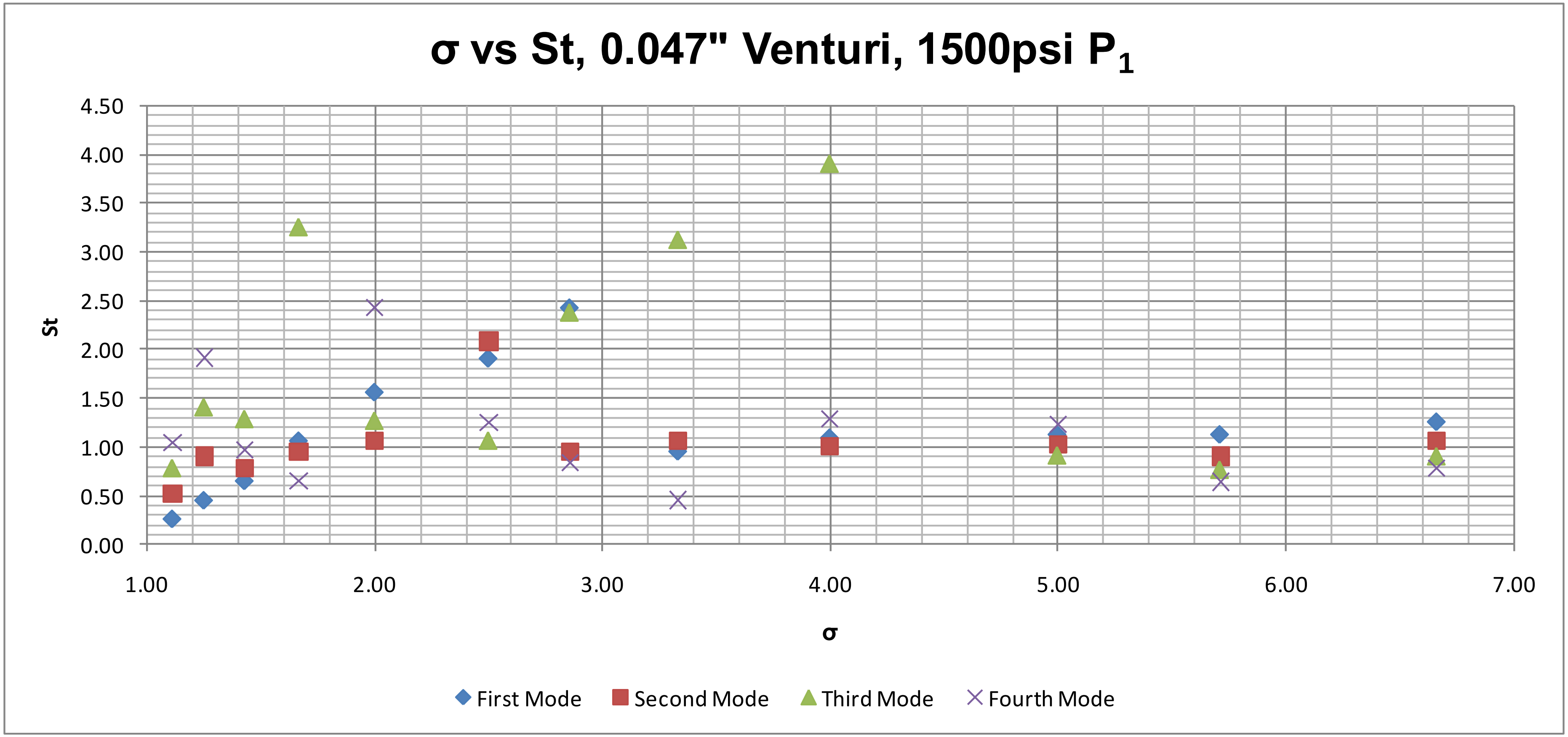


Fig24.

(Phuoc Hai Tran AFRL/RZSE, 2011)

Frequency Signature

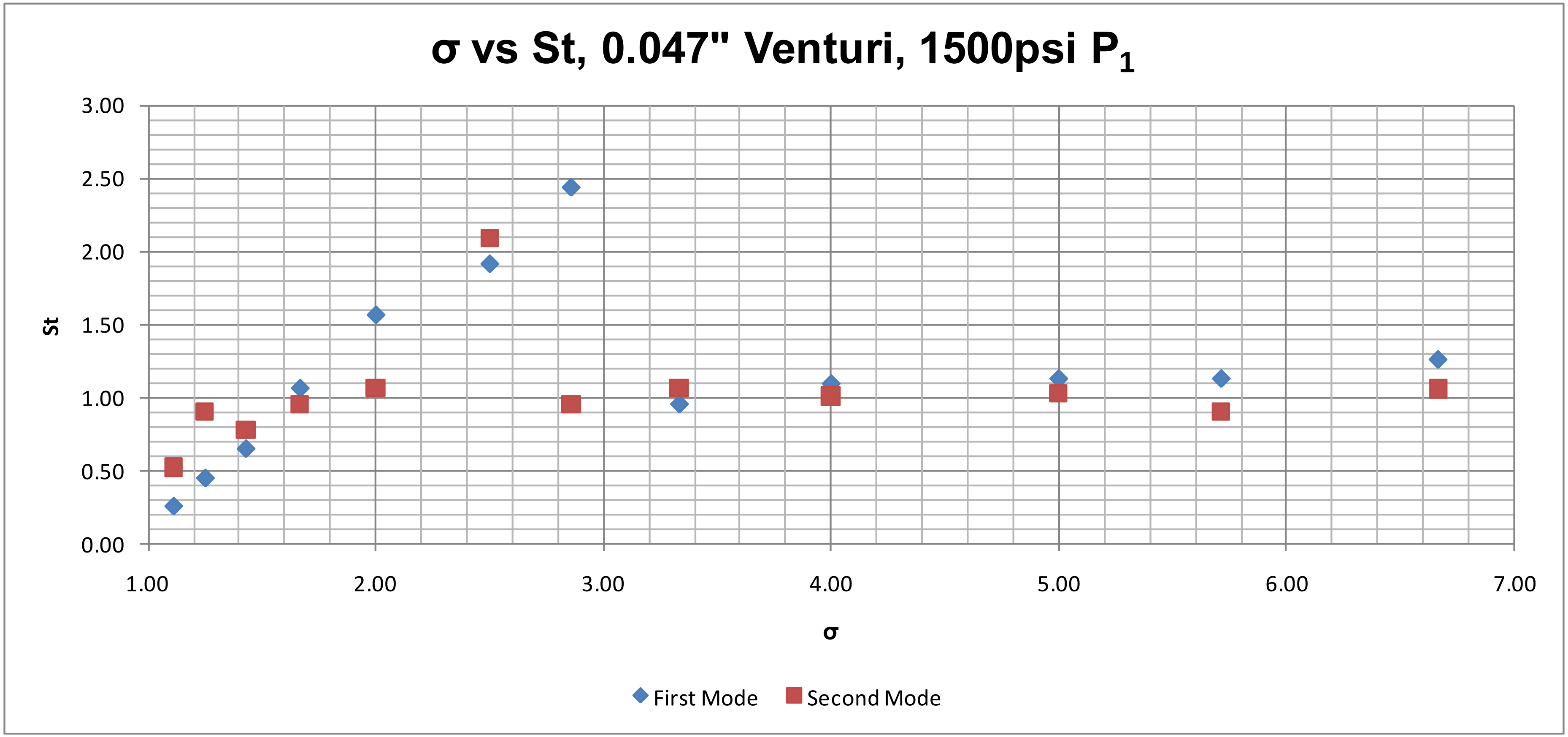


Fig25.
(Phuoc Hai Tran AFRL/RZSE, 2011)

Frequency Signature

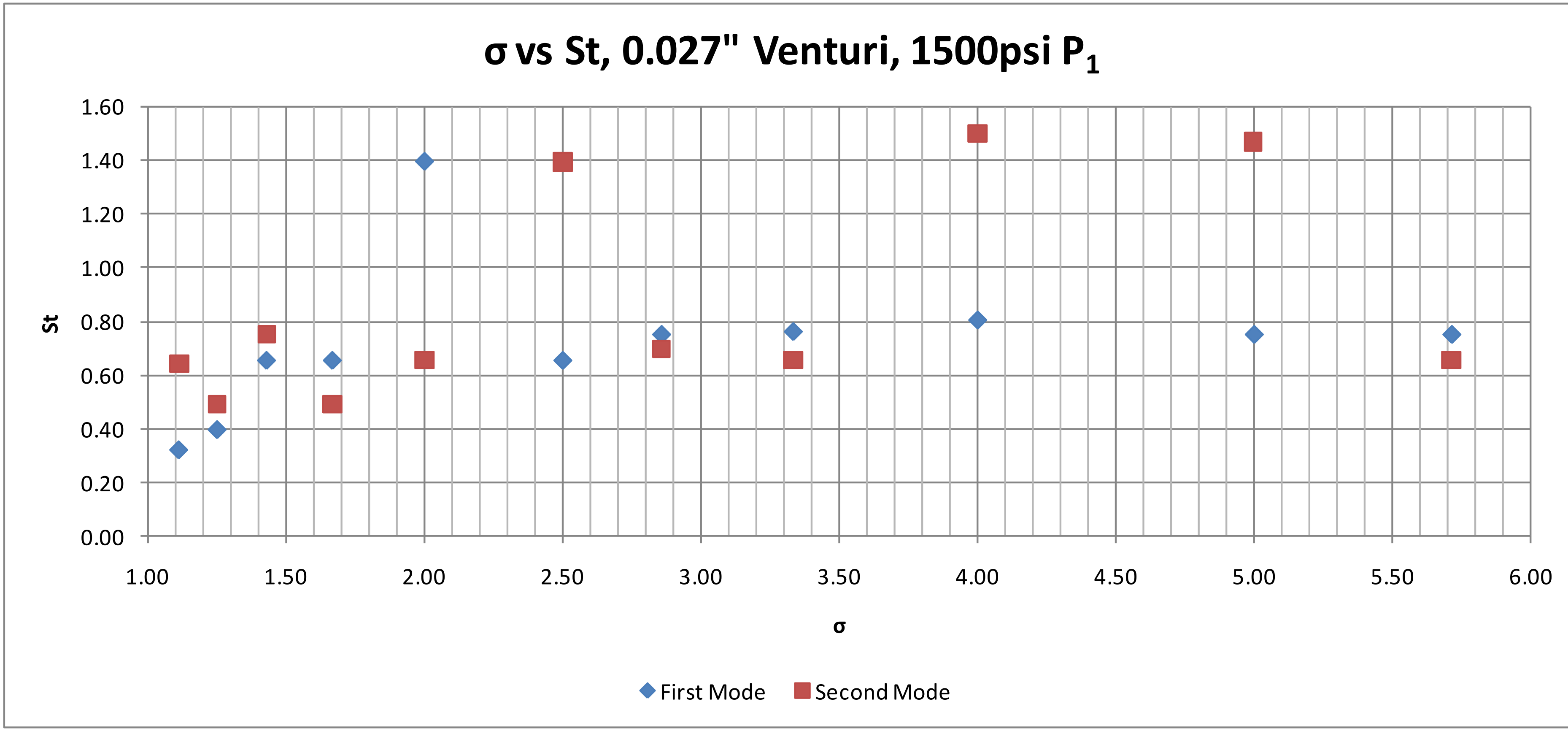


Fig26.
(Phuoc Hai Tran AFRL/RZSE, 2011)

Frequency Signature

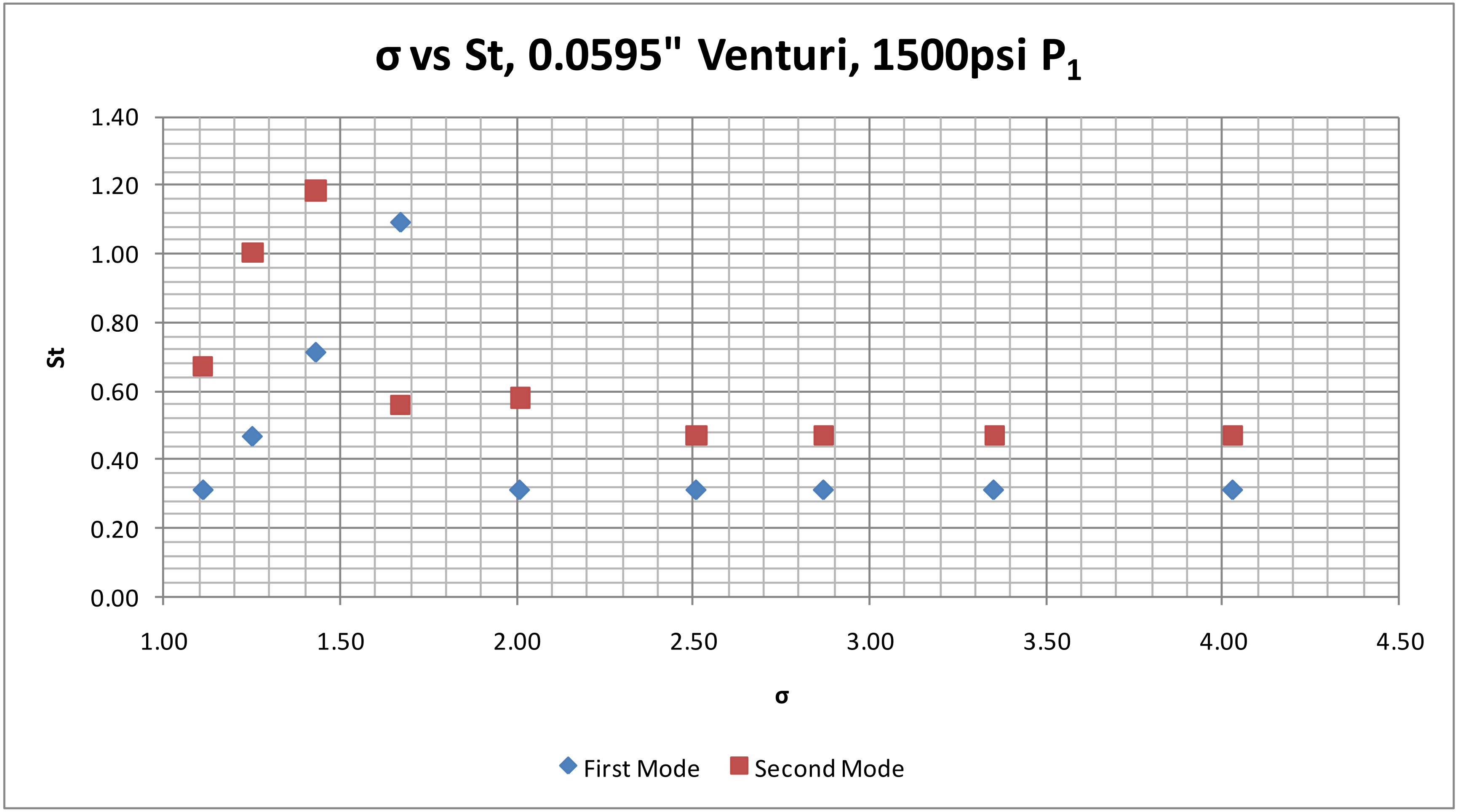


Fig27.
(Phuoc Hai Tran AFRL/RZSE, 2011)

Frequency Signature

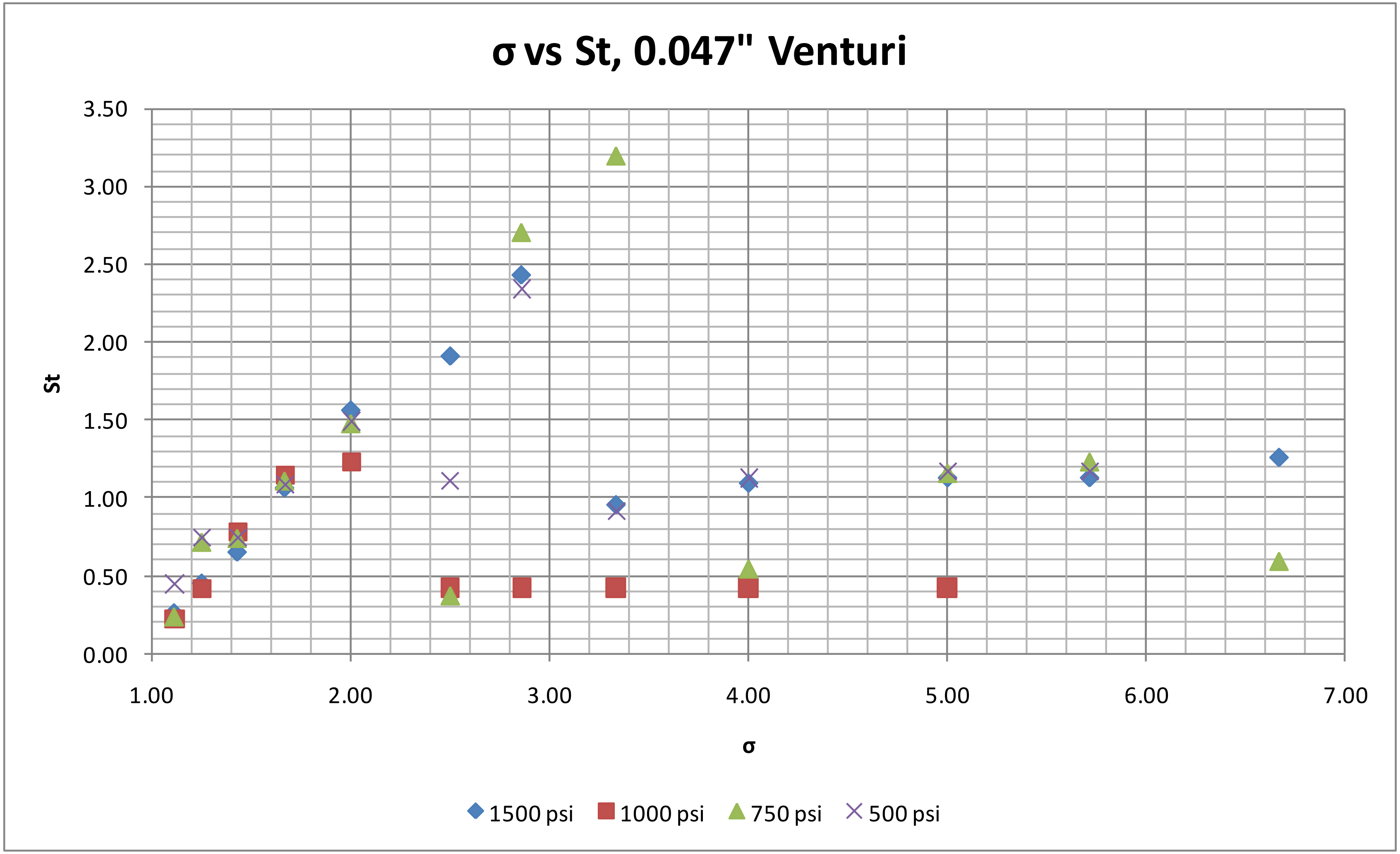


Fig28.
(Phuoc Hai Tran AFRL/RZSE, 2011)

Frequency Signature

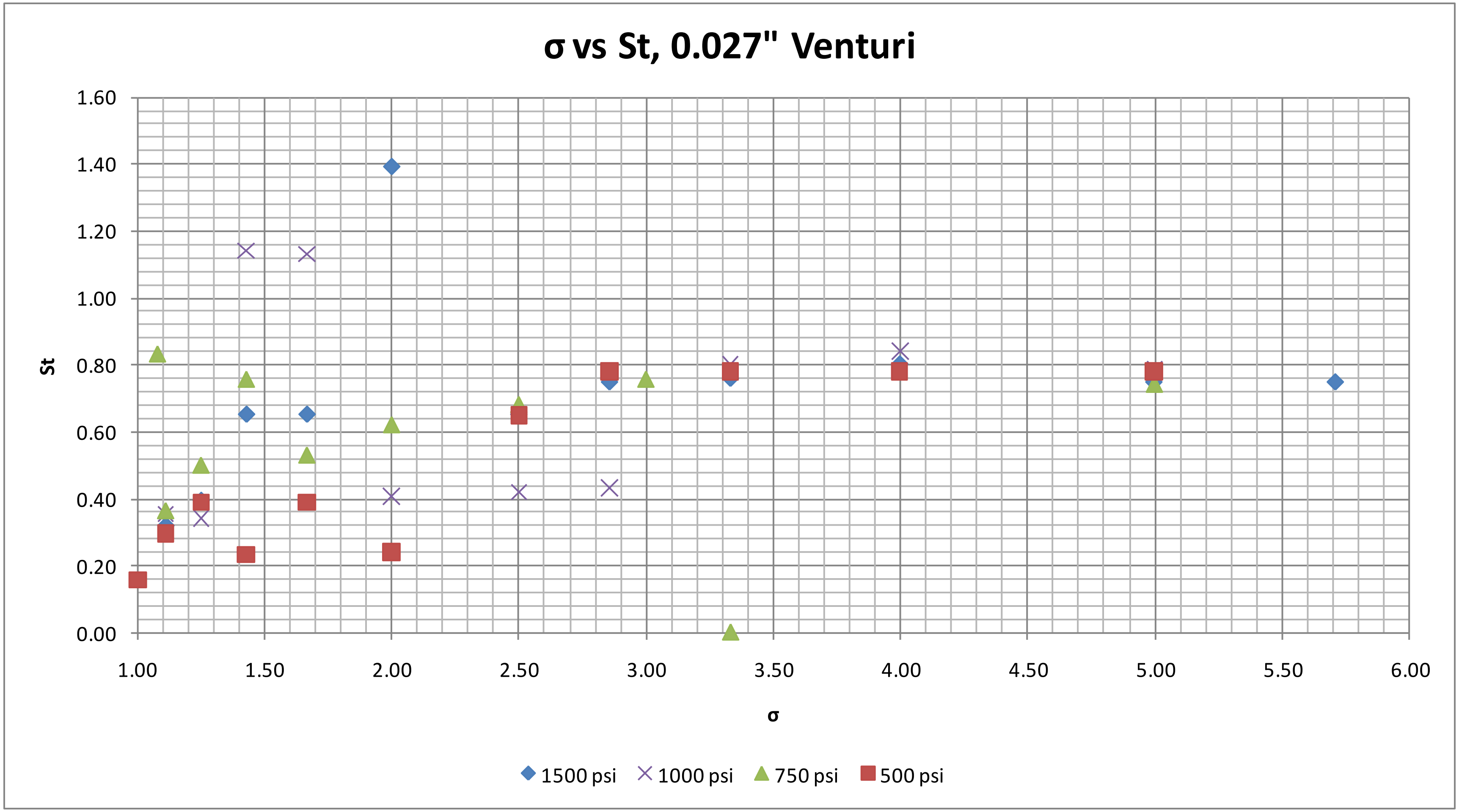


Fig29.
(Phuoc Hai Tran AFRL/RZSE, 2011)

Frequency Signature

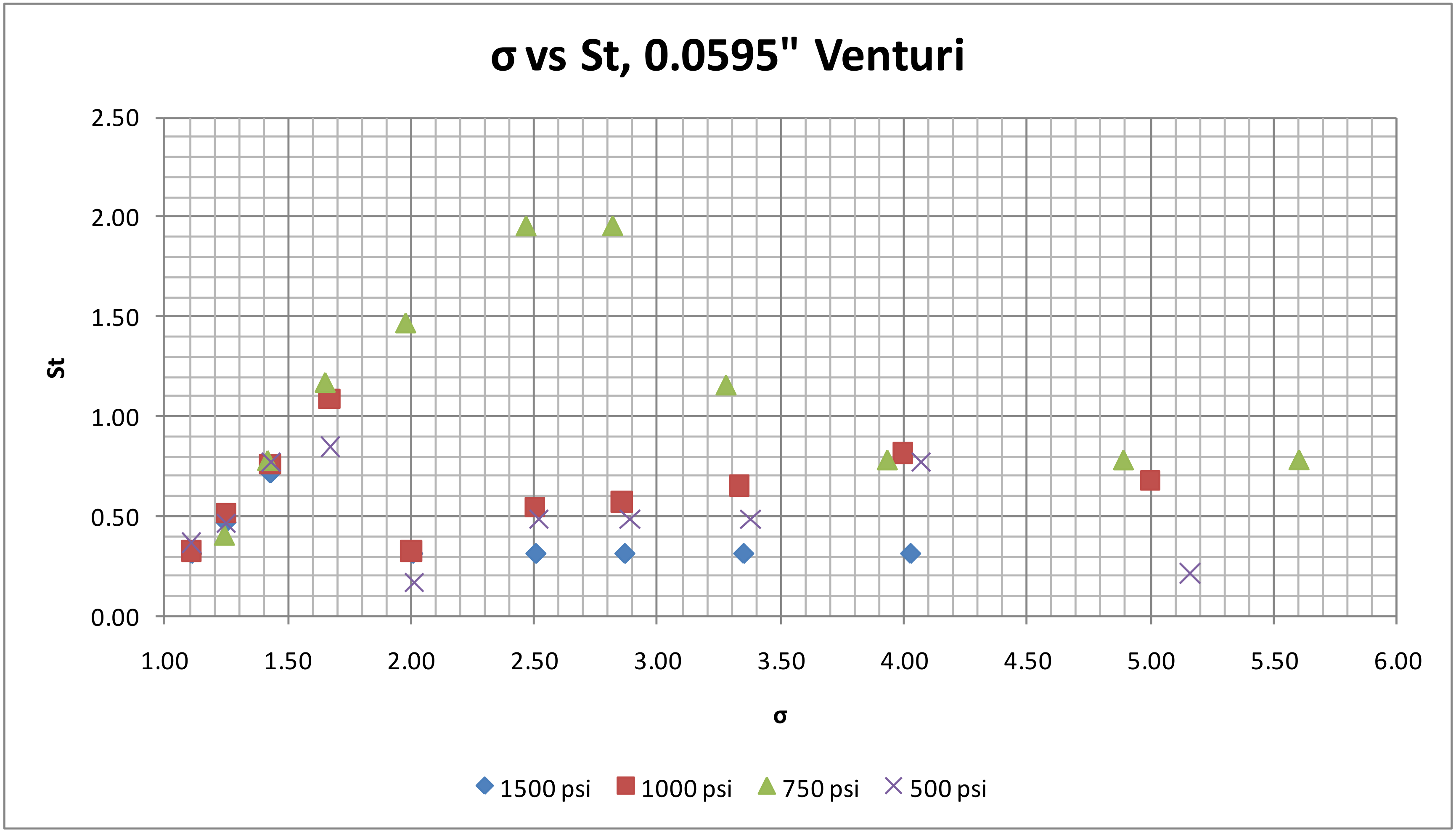


Fig30.

(Phuoc Hai Tran AFRL/RZSE, 2011)

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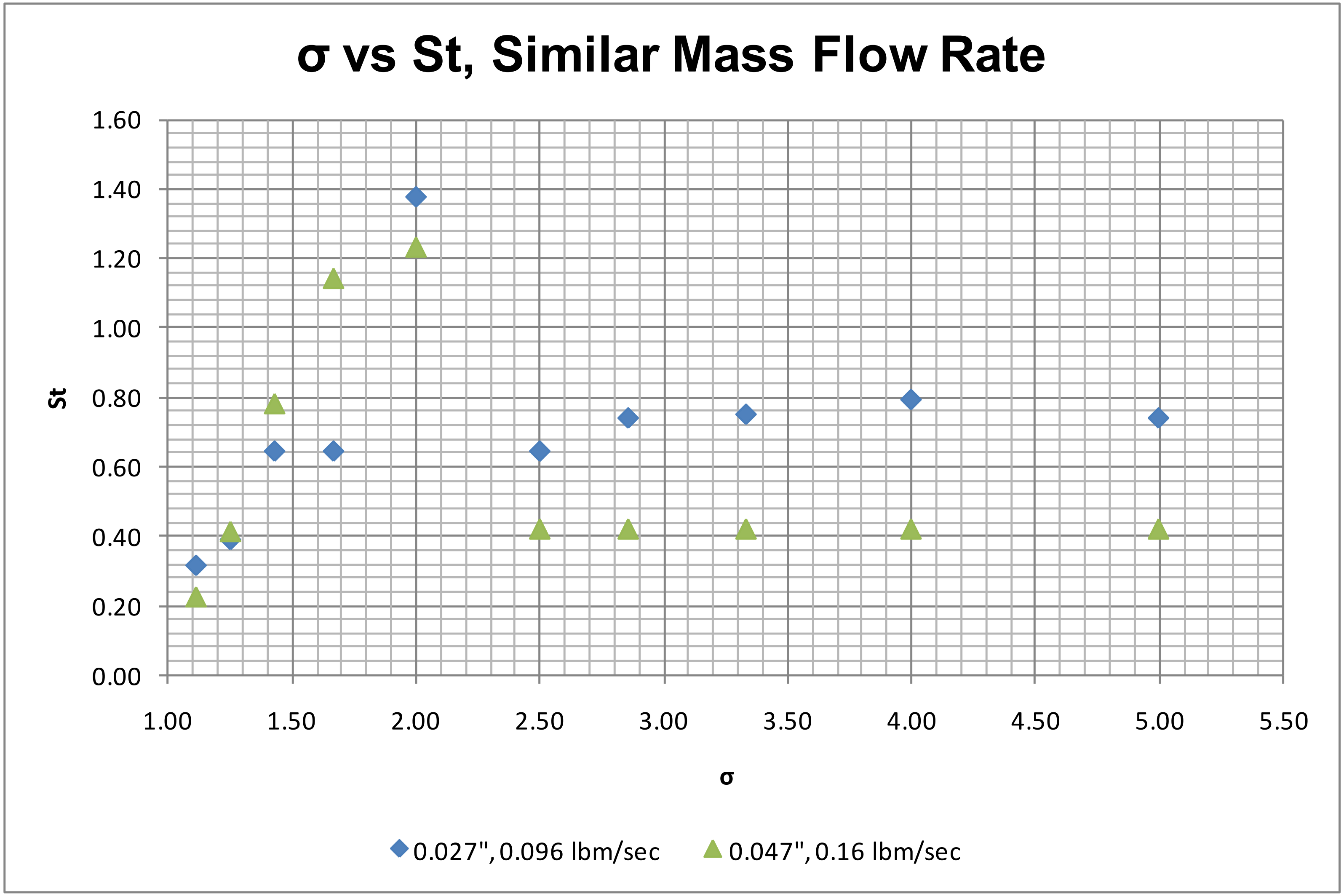


Fig31.

(Phuoc Hai Tran AFRL/RZSE, 2011)

Frequency Signature

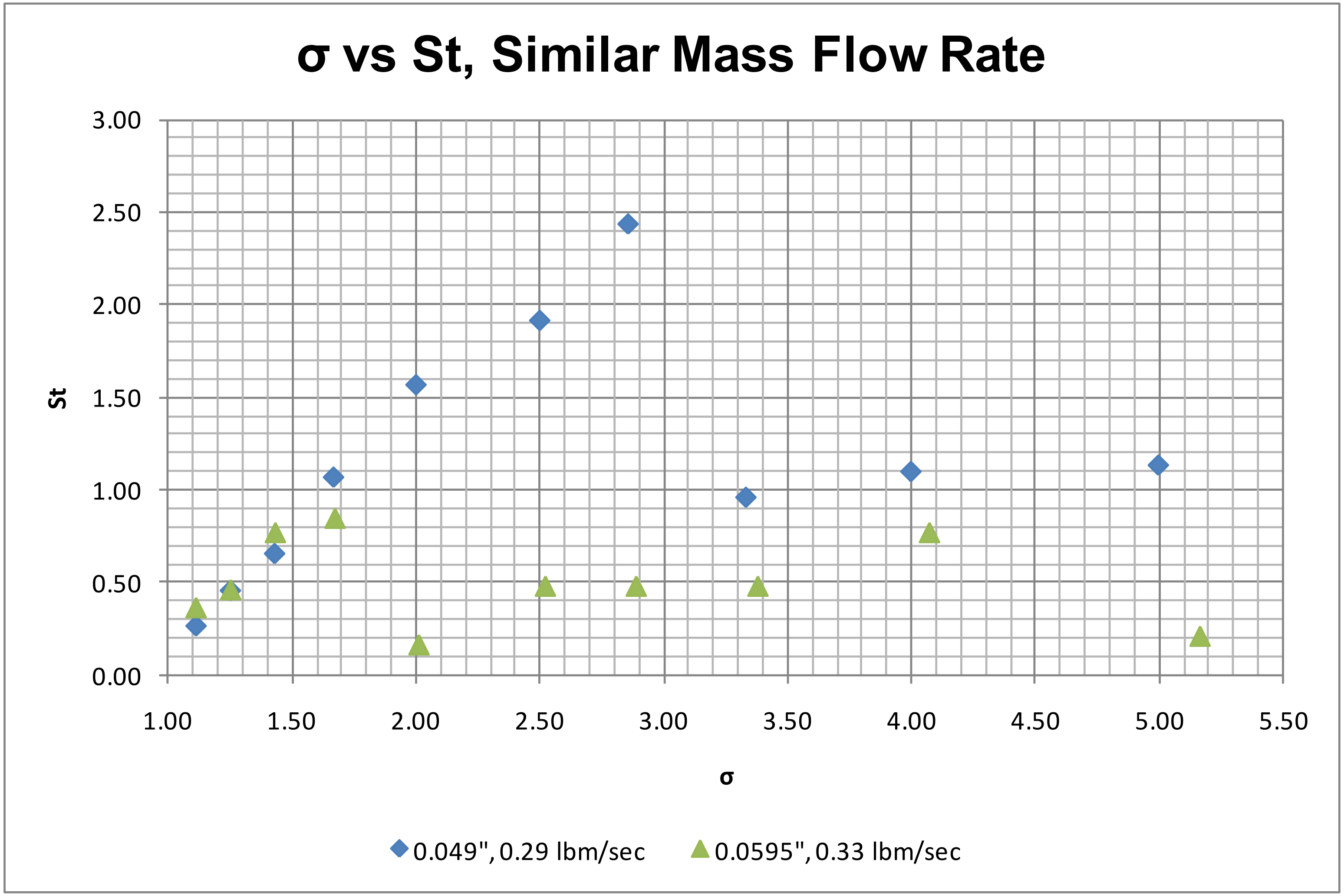


Fig32.

(Phuoc Hai Tran AFRL/RZSE, 2011)

Conclusions

Conclusions

- **Acoustic disturbances caused by cavitating venturi not well attenuated**
  - Only 4% decrease in pressure wave amplitude from near to far downstream stations at the most
- **Strouhal numbers found to be closer to 0.8 (or 0.4 depending on harmonic)**
- **Complex frequency signatures vary over the operating regime of a cavitating venturi**

Future Work

- **Explore selection of fundamental quantities and comparisons for Strouhal number**
- **Examine effect of venturi design**
- **More closely represent a real system**
- **Examine cause of complex frequency signatures, especially in the high range (10,000 – 20,000 Hz)**
- **Examine cause for anomalous C_d for 0.0595” Venturi**

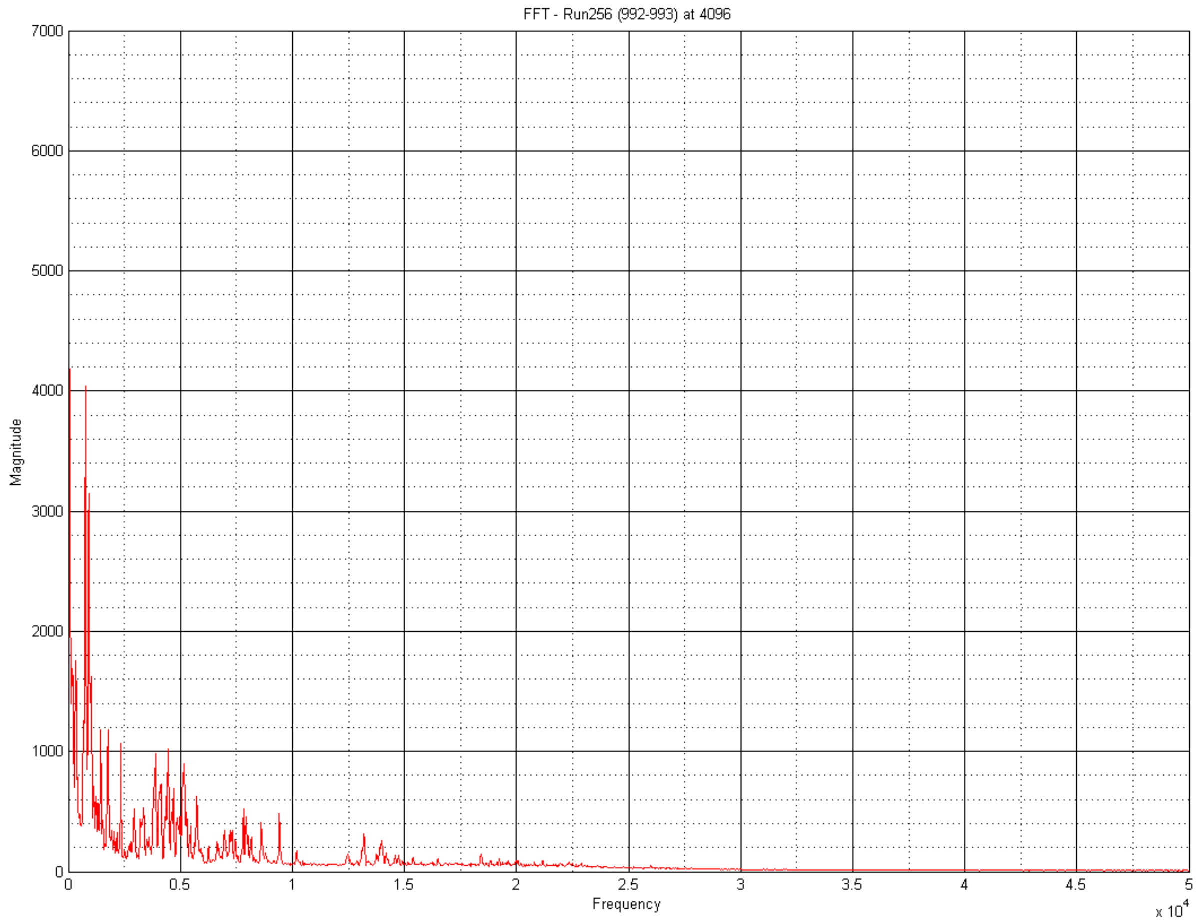
Internship Experience Summary

Engage in professional research engineering

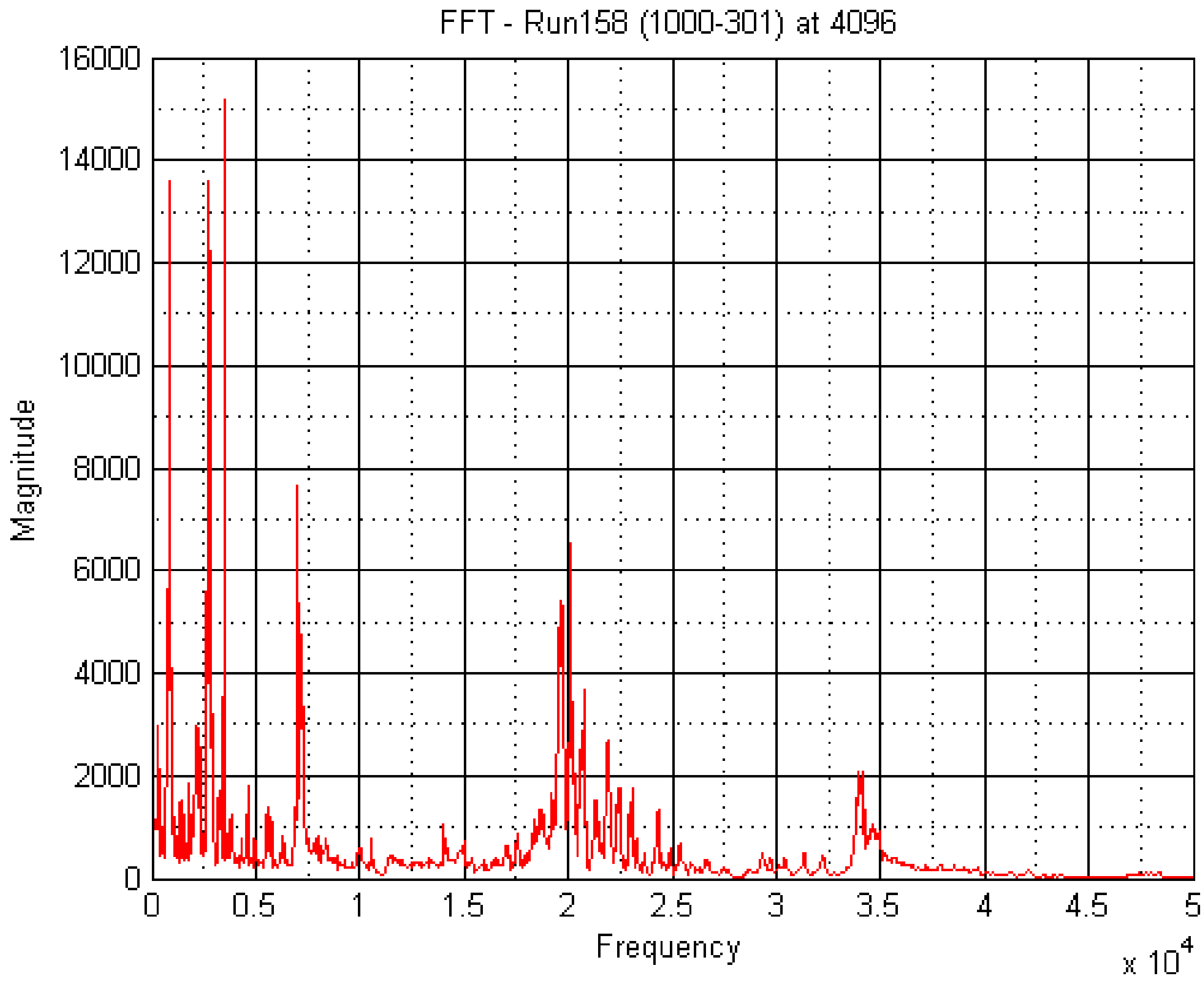
- **Logistics**
  - How to interact with engineers, technicians, and industry for project completion
  - How to prepare and present technical information
- **Research**
  - How to effectively survey literature
  - How to design, prepare, and conduct an experiment
  - How to perform data analysis
    - Spectral Analysis and FFT Frequency Spectra

Questions?

Upstream Effects



Upstream Effects



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Upstream Effects